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LCA OF WASTE MANAGEMENT SYSTEMS

Discussion on methods to include prevention activities in waste management LCA

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Abstract
Purpose Waste prevention has been assigned increasing attention worldwide during recent years, and it is expected to become one of the core elements of waste management planning in the near future. In this framework, this paper presents and discusses two possible LCA approaches for the evaluation of the environmental and energetic performance of municipal solid waste (MSW) management systems which include the effects of waste prevention activities.
Methods The two approaches are conceived for the comparison of waste management scenarios including waste prevention activities with baseline scenarios without waste prevention. For both of them, the functional unit is defined and the system boundaries are described with reference to different typologies of waste prevention activities identified in an extensive review. The procedure for the calculation of the LCA impacts of scenarios is also reported and an example illustrating the processes to be included in system boundaries for a specific waste prevention activity is provided.
Results and discussion The presented approaches lead to the same result in terms of difference between the LCA impacts of a waste prevention scenario and of a baseline one. However, because of the partially different upstream system boundaries, different values of the impacts of single scenarios are obtained and the application of the two approaches is more suitable in different situations and in analyses with different purposes. The methodological aspects that can complicate the applicability of the two approaches are discussed lastly.
Conclusions The environmental and energetic performance of MSW management scenarios including waste prevention activities can be evaluated with the two LCA approaches presented in this paper. They can be used for many purposes such as, among the most general, evaluating the upstream and downstream environmental consequences of implementing particular waste prevention activities in a given waste management system, complementing waste reduction indicators with LCA-based indicators and supporting with quantitative evidence the strategic and policy relevance of waste prevention.

Keywords Integrated municipal solid waste (MSW) management systems · Life cycle assessment (LCA) · Waste hierarchy · Waste prevention · Waste prevention activities

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1 Introduction

Over the last two decades, the life cycle assessment (LCA) methodology has widely been used to evaluate the environmental and energetic performance of real or fictional integrated municipal solid waste (MSW) management systems (e.g. among the most recent, Antonopoulos et al. 2012; Blengini et al. 2012; Giugliano et al. 2011; Pires et al. 2011; Bovea et al. 2010; De Feo and Malvano 2009; Liamsanguan and Gheewala 2008; Buttol et al. 2007). Nevertheless, as also recently reported by Saner et al. (2012), waste prevention has rarely been included in such evaluations, despite it is indicated as the most favourable option in the so-called waste hierarchy (e.g. by the Waste Framework Directive for the European Union; European Parliament and Council 2008). Exceptions include the recent studies by Gentil et al. (2011), Matsuda et al. (2012) and, partially, Slagstad and Brattebø (2012). In Gentil et al. (2011), the environmental performance of the waste management system of an hypothetical European municipality, which includes the partial prevention of food waste (through reduction of food surplus), unsolicited mail (through their refusal) and beverage packaging (through the use of refillable bottles), are compared with the performance

of the same system without waste prevention. Matsuda et al. (2012) calculated greenhouse gases emissions associated with different household waste management scenarios for the city of Kyoto, and one of these included a reduction of edible food loss as a consequence of the introduction of separate collection of the food waste. Finally, Slagstad and Brattebø (2012) compared five scenarios for the waste management system of a new urban settlement under planning in Trondheim, with and without the partial prevention of all the waste fractions entering the system, although without referring to any particular waste prevention activity. For this reason, only the consequences on the performance of the waste management system (intended as the system including the management processes of the different MSW streams generated in the analysed scenarios) were evaluated. Conversely, the possible upstream benefits associated with the prevention of the different waste fractions, as well as the upstream loads possibly associated with the implementation of waste prevention activities were not taken into account in their study.

It seems that waste prevention activities have rarely been included in LCA of MSW management systems for a number of reasons. First of all, the methodology has originally been conceived to compare the environmental performance of different systems (commonly indicated as integrated waste management systems) for the collection, treatment and disposal of the MSW arising, in a given amount and composition, from a given area (McDougall et al. 2001). For this reason, as also pointed out by Ekvall et al. (2007) traditional waste management LCA has been developed with some inherent methodological characteristics (that will be better detailed in Section 3) that prevent its utilisation for the comparison of scenarios where different overall amounts of waste are generated, as in the case where some of them include waste prevention activities. Moreover, accounting for waste prevention activities can make the assessment more complicated since upstream processes of the life cycle of the prevented waste or of the life cycle of other goods and services are likely to be affected, thus needing to be included in the system boundaries. Finally, as also stated by Wilson et al. (2010), attention so far was mainly oriented on finding environmentally sound strategies for waste treatment and disposal, while now that high recycling rates are generally achieved and incineration with energy recovery is generally well established in most developed countries, increasing attention needs to be devoted to waste prevention.

In order to 'facilitate the comparison of MSW management scenarios incorporating waste prevention and the various methods of waste treatment', Cleary (2010) has recently proposed a conceptual model named Waste Management and Prevention (*WasteMAP*) LCA. Another method, for certain aspects similar to that of Cleary (2010), has also more recently been described and applied by Gentil et al. (2011) for their analysis (see Section 4 for a brief description of both the approaches).

According to the current legislation (European Parliament and Council 2008), Member States of the European Union are requested to prepare national waste prevention programmes, possibly integrated within waste management plans. Therefore, waste managers and policy makers will probably have to increasingly deal with the waste prevention issue in their planning activities in the near future and the availability of a unique LCA tool capable to evaluate the environmental and energetic performance of waste management systems which, besides conventional treatments, include the effects of waste prevention activities is deemed to be of use. Moreover, Gheewala (2009) included the inability of traditional waste management LCA to account for the effects of waste prevention activities, among the limitations to the applicability of the methodology as a decision support tool in waste management planning and policy making, to be addressed in further researches.

In this framework, this article presents and discusses two possible LCA approaches for the evaluation of the environmental and energetic performance of integrated MSW management scenarios that include waste prevention activities and the different waste treatment options. A discussion on the methodological aspects that prevent traditional waste management LCA from addressing waste prevention activities and a review of the amendments and of the approaches proposed so far in the scientific literature in the attempt to overcome this limitation are also initially reported. In this way a structured framework of the state of the art on a theme only sparsely addressed so far is provided.

2 Typologies of waste prevention activities

A review of the major typologies of MSW prevention activities is reported in this section, representing an essential preliminary stage for the discussion of the modelling approaches presented in this paper.

Waste prevention is defined by the European Waste Framework Directive 2008/98/EC (European Parliament and Council 2008) as measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste, including through the re-use of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health and (c) the content of harmful substances in materials and products.

By definition waste prevention activities are therefore classified between those aimed at achieving a quantitative prevention (reduction of the amount of the generated waste) and those aimed at achieving a qualitative prevention (reduction of the hazardousness of the generated waste). Reuse and lifespan extension of goods are included among quantitative waste prevention activities, since they ultimately lead to a reduction of the amount of generated waste.

Focussing on quantitative waste prevention, the major typologies of MSW prevention activities identified after an extensive

review are reported in Table 1 together with some examples for each of them. Most relevant consulted sources are ACR+ (2010), Federambiente (2010), European Commission (2012), European Commission DG Environment (2010), Salhofer et al. (2008), Regione Lombardia (2009), Cox et al. (2010) and Sharp et al.(2010).

As it can be noticed, while some activities aim at reducing waste generation thanks to a reduction in the consumption (or wastage) of a given good or service (types 1 and 2 activities), in other cases waste prevention is achieved through a more complex mechanism, based on the replacement of a given good or service with a less waste-generating equivalent one (types 3 to 6 activities). Reuse of disposable or durable goods (types 7 and 8 activities) and lifespan extension of existing or new durable goods (types 9 and 10 activities) complete the framework.

Regarding the environmental consequences of waste prevention activities, in the case of a simple reduction in the consumption of a given good or service, the environmental impacts associated with its whole life cycle are generally avoided. When a replacement with a less waste-generating equivalent good or service takes place, additional impacts associated with the whole life cycle of such a less waste-generating good or service are instead also involved. Finally, reuse and lifespan extension of existing goods generate environmental impacts by increasing their use phase, while avoiding the impacts from producing, using and disposing of one or more equivalent new good(s) (Joint Research Centre of the European Commission 2011).

3 Methodological limitations of traditional waste management LCA in addressing waste prevention activities

There are two interrelated methodological aspects that prevent traditional waste management LCA from accounting for the effects of waste prevention activities: the choice of the functional unit and the resulting definition of the system boundaries. First, the functional unit is often defined, for all of the compared scenarios, as the management (collection and treatment) of a given amount (e.g. 1 tonne) of waste, with a given composition, representative of the real or fictional geographical area under investigation (e.g. Gunamantha 2012; Menikpura et al. 2012; Abduli et al. 2011; Koci and Trecakova 2011; Kaplan et al. 2009; Rigamonti et al. 2009; Chaya and Gheewala 2007; Bovea and Powell 2006; Hong et al. 2006; Weitz et al. 1999). In other cases (e.g. Koroneos and Nanaki 2012; Zhao et al. 2011; Zhao et al. 2009; Buttol et al. 2007; Muñoz et al. 2004; Beccali et al. 2001), it is more generally defined as the management of the waste generated in a given geographical area over a given time period (e.g. one specific year). The corresponding amount is then considered as the constant input waste to all of the compared scenarios. Therefore, in principle, the utilisation of a functional unit based on a given amount of waste to be managed does not allow for the comparison of scenarios where different overall amounts of waste are generated and have to be managed, as in the case where some of them include waste prevention activities (Ekvall et al. 2007).

Secondly, being the amount of generated waste identical in all of the analysed scenarios, comparative assessments are generally simplified by defining the system boundaries based on the so-called 'zero burden' assumption (Ekvall et al. 2007). This means that all the processes and activities occurring before the moment in which products become waste (upstream processes/activities) are usually excluded from the system boundaries, since they are common to all scenarios. On the contrary, when waste prevention activities are included in the assessment, both different amounts of waste are generated in the analysed scenarios and the magnitude or the typology of some of the upstream processes/activities is likely affected. The 'zero burden' assumption is, in general, no longer valid and at least those parts of upstream processes/activities which differ among scenarios should be included in the system boundaries (Finnveden 1999). Otherwise the impacts of a scenario that produces less waste are overestimated compared to the others (Finnveden 1999) when waste prevention is actually achieved without increasing the overall upstream impacts. Even worse, when the 'avoided burden method' (Finnveden et al. 2009) is employed to solve the multifunctionality of recovery processes and negative values of the LCA impact indicators are obtained, a reduction in waste generation would be paradoxically associated with a reduction in the downstream environmental benefits.

4 Possible amendments to traditional waste management LCA proposed in the literature

In order to overcome the limitation imposed by the utilisation of a functional unit based on a given quantity of waste to be managed, Ekvall et al. (2007) suggest to define a functional unit such as "the annual quantity of waste generated in a geographical area", without specifying any amount.

Doing so, it would be possible to compare scenarios where different amounts of waste are generated, but, as observed in Section 3, the 'zero burden' assumption is, in general, no longer valid. Therefore, the authors conclude reasonably wondering whether the environmental burdens associated with the upstream processes of the life cycle of all the products that become waste should be taken into account.

Trying to answer this question, Cleary (2010) has more recently claimed that a complete abandonment of the 'zero burden' assumption may not be necessary, and proposed an approach named as *WasteMAP* LCA (Waste Management and Prevention LCA), employable to compare MSW management scenarios including waste prevention activities and

Table 1 Major reviewed typologies of municipal solid waste prevention activities and respective examples

Typology of waste prevention activities		Examples	Prevented MSW (waste goods or packaging)	Substitutive goods or packaging generated as additional MSW to be managed
Reduction in the consumption of goods or services	1. Reducing the consumption of goods by citizens (without reducing the consumption of the service originally provided by those goods)	Reducing domestic consumption of paper through double-sided printing and copying	A given amount of white graphical paper depending on the number of double-sided printed documents	None
		Renting or borrowing/lending of goods instead of purchasing new ones (e.g. infrequently used clothes and textiles, office furniture, toys, books, home and garden tools, party/event decorations and supplies, paints etc.)	A given amount of new equivalent finished products depending on the number of borrowed/lent products	None
	2. Reducing the wastage of goods (unnecessary to the consumer)	Reducing food waste (unconsumed or partially consumed food and leftovers) by improving one's own food purchasing and storage behaviour, avoiding leftovers etc.	A given amount of food waste depending on the number of people that will change their behaviour and the specific generation of food waste	None
		Reducing the delivery of unsolicited mail and advertising material by hanging dissuasive stickers on mailboxes, subscribing to mail preference services etc.	A given amount of printed paper and/or brochures delivered by post to households depending on the number of them participating in the initiatives and the specific generation of unsolicited mail	None
Development and/or use of less waste-generating goods or services to provide a given function	3. Reducing the amount of materials used for the manufacturing or packaging of a good through its more efficient design (without reducing its performance, e.g. the amount of packaged product damaged or lost is not increased)	Reducing the amount of steel used to manufacture a washing machine	One or more heavier washing machine(s) depending on the number of lighter ones that will be used	One or more lighter washing machine(s)
		Reduction in the amount of packaging material used per unit mass of packaged product, like:		
		Lightweighting of beverage bottles (without reducing their strength)	A given amount of heavier beverage bottles depending on the volume of beverage packaged in lighter bottles that will be consumed	A given amount of lighter beverage bottles
		Increasing volume capacity of containers	A given amount of smaller containers depending on the amount of product packaged in bigger containers that will be consumed	A given amount of bigger containers
	4. Use of an unpacked good instead of a packed one	Drinking of public network water instead of bottled water	A given amount of water bottles proportional to the volume of public network water that will be consumed for drinking purposes	One or more reusable jug(s) or bottle(s)
	5. Development and/or use of a reusable good or of a good provided in a reusable packaging instead of a disposable good or of a good provided in a disposable packaging	Distribution and use of water or other beverages packaged in refillable bottles rather than packaged in one-way bottles	A given amount of one-way plastic or glass bottles proportional to the volume of beverage that will be consumed from refillable bottles	A given amount of refillable glass or plastic bottles
		Distribution and use of draught liquid detergents (to be packed in refillable flacons) instead of those packaged in disposable flacons	A given amount of disposable plastic flacons proportional to the volume of draught detergents that will be purchased	A given amount of reusable plastic flacons
		Distribution and use of loose dry food products (to be packed in lightweight plastic or paper bags) instead of those provided in disposable packaging	A given amount of disposable packaging proportional to the amount of loose dry food products that will we purchased	A given amount of (reusable) lightweight plastic or paper bags
		Use of returnable cardboard boxes for transport of goods rather than disposable ones	A given amount of disposable cardboard boxes proportional to the number of shipments performed with the same reusable boxes	A given amount of reusable cardboard boxes
		Use of reusable nappies rather than disposable ones	A given amount of disposable nappies proportional to the number of children that will use reusable ones	A given amount of reusable nappies
		Use of electric hand-dryers rather than paper bath-towels	A given amount of paper bath-towels proportional to the number of hand pairs dried with electric hand-dryers	One or more electric hand-dryer(s)
		Use of reusable shopping bags rather than disposable ones	A given amount of disposable shopping bags proportional to the number of purchasing activities performed with the same reusable bags	A given amount of reusable shopping bags

Table 1 (continued)

Typology of waste prevention activities		Examples	Prevented MSW (waste goods or packaging)	Substitutive goods or packaging generated as additional MSW to be managed
		Use of reusable crockery rather than disposable ones	A given amount of disposable crockery proportional to the number of meals served with reusable crockery	A given amount of reusable crockery
		Distribution and purchase of loose fruits and vegetables rather than packaged within disposable plastic trays and films, disposable plastic containers etc.	A given amount of disposable packaging proportional to the amount of loose fruits and vegetables that will be purchased	A given amount of paper or plastic bags
	6. Use of a digital good instead of a disposable one	Substitution of on-line brochures with information on commercial offers by retailers for printed ones	A given amount of printed brochures delivered by surface mail to the citizens depending on the number of the ones that would have traditionally been printed on paper	None[a]
		Reading of on-line newspapers instead of printed ones	A given amount of printed newspapers depending on the number of the ones that will be read on-line	None[a]
		Digitalisation of documentation in companies and public administration (use of electronic archives etc.)	A given amount of printed documents depending on the number of the ones whose life cycle will be digitalised	None[a]
Reuse of goods	7. Direct reuse of disposable goods or packaging by the owner (private citizens or organisations) in substitution of disposable or durable goods or packaging	Reuse of a disposable shopping bag, of a disposable glass jar, of a one-way glass or plastic bottle etc.	A given amount of identical new disposable goods (e.g. shopping bags) depending on the number of reused goods and the number of times they are reused, or a given amount of equivalent new durable goods (e.g. jars) depending on the number of reused goods and the ratio between the duration of their second life and the average lifespan of equivalent new goods	None
	8. Reuse of durable goods through second-hand selling and purchasing, donation and exchange	Selling/purchase in second-hand markets, donation to charities and people in need or exchange of durable goods such as clothes and textiles, furniture, electrical and electronic equipment, toys, books, bicycles, sport and fitness equipment, baby and nursery products and accessories, home and garden tools, party/event decorations and supplies etc.	A given amount of equivalent new durable goods depending on the number of reused goods and the ratio between the duration of their second life and the average lifespan of equivalent new goods	None
Extension of the lifespan of durable goods	9. Extension of the lifespan of existing durable goods by citizens or repair centres	Repairing of durable goods such as clothes and textiles, furniture, electrical and electronic equipment, bicycles, sport equipment, home and garden tools etc., by citizens or repair centres	A given amount of equivalent new durable goods depending on the number of repaired goods and the ratio between the duration of their second life and the average lifespan of equivalent new goods	None
		Keep appliances in good working order by following manufacturers' suggestions for proper operation and maintenance	A given amount of equivalent new durable goods depending on the number of goods the lifespan of which has been extended and the ratio between the duration of their additional life and the average lifespan of equivalent new goods	None
	10. Extension of the useful life of durable goods by producers	Extension of the useful life of domestic appliances through a more efficient design	A given amount of shorter-lasting domestic appliances depending on the number of used longer-lasting domestic appliances and on the ratio between the duration of their lifespan and that of substituted shorter-lasting domestic appliances	Longer-lasting domestic appliances effectively used

[a] Any additional waste is not generated in place of substituted disposable good(s) only under the assumption that the electronic devices required to use the substitutive digital goods are already owned by the citizens or organizations participating in the prevention activities. Nevertheless, even in this case, a portion of the life cycle of such devices and of the associated MSW generation may be allocated to the use of substitutive digital goods

the various methods of waste treatment. According to this approach, only the upstream components of the product systems affected by waste prevention activities need to be included within the system boundaries.

This model is mainly conceived to deal with waste prevention activities based on dematerialisation, i.e. activities that do not affect the amount of services supplied to the citizens of the area under study. The model adopts a *primary functional unit* depicting ‘the amount (mass or volume) of material addressed by the MSW management system on an annual basis’, which is identical for all the scenarios and is equal to the sum of the amount of waste prevented and the amount of waste collected and treated under each scenario. Moreover, the definition of a *secondary functional unit* is suggested, in order to ‘ensure that MSW management scenarios subject to comparison will supply functionally equivalent product services to the residents of the municipality’ under study.

Scenarios including waste prevention activities based on a reduction in products/services consumption ‘without product service substitution’ cannot be compared with a reference scenario on the basis of a complete functional equivalence using the *WasteMAP* LCA model, since ‘there would be no replacement product service provided’.

An approach somehow similar to that proposed by Cleary (2010) is the one adopted by Gentil et al. (2011). In order to compare the environmental performance of a waste management scenario including different waste prevention activities with a baseline scenario without waste prevention, the authors define an apparently traditional functional unit, i.e. ‘the service of managing 100,000 mt of average MSW from a fictional European municipality’. This seems to be in contrast with the introduction of waste prevention, which involves a reduction in the amount of waste generated and to be managed. Actually, in the waste prevention scenario, prevented waste fractions are considered as virtual waste flows that are not subjected to any transformation within the traditional waste management system and, hence, do not involve any downstream environmental burden. Therefore, similarly to the approach of Cleary (2010), the functional unit is effectively composed of the amount of waste actually generated and the amount of prevented or ‘virtual’ waste, the sum of which is identical in both the compared scenarios.

According to the authors, the use of a so defined functional unit allows in principle the practitioner to keep excluding upstream processes in the life cycle of all the waste fractions, since the same amount and composition of waste (real or virtual) enter the management system in the compared scenarios (in which constant consumption levels are assumed). Nevertheless, extraction, manufacture, distribution and use of prevented waste fractions are likely avoided and will have to be included in the system boundaries. Therefore, in practice, in waste prevention scenarios the virtual flows of prevented waste are included in the mass balance of the system and routed to a fictional burden free waste management technology, which is credited with the avoided production (extraction, manufacture, distribution and use) of the prevented waste fractions themselves.

No explicit mention is made by the authors about the need of also accounting for the additional upstream burdens possibly involved because of the implementation of waste prevention activities, due, for instance, to the consumption of alternative products or services. Nevertheless, it seems that these additional burdens have been taken into account in the case study described in their paper.

Finally, some recommendations about the processes to be included in the system boundaries to evaluate the environmental performance of waste prevention activities are provided in the guidelines prepared by the Joint Research Centre on behalf of the European Commission (Joint Research Centre of the European Commission 2011). In particular, they state that all the processes upstream of collection and treatment should be included in the system boundaries whenever they are modified by waste prevention activities. Such modified processes may be excluded only if changes are negligible and do not significantly affect the results.

5 Modelling approaches

Two possible approaches (*Approach 1 and Approach 2*) are identified and described in this section, for the LCA-based comparison of the environmental and energetic performance of integrated MSW management scenarios that foresee the implementation of one or more waste prevention activity(ies) (in the following *waste prevention scenarios*) with that of scenarios in which no waste prevention activities are undertaken and the same amount of waste is generated (in the following *baseline scenarios*).

5.1 Perspective on waste prevention activities

According to the first approach (*Approach 1*), waste prevention is considered to be an actual waste management method. The amount of waste managed through conventional treatments (i.e. mechanical and biological treatments, recycling, thermal treatments and landfilling) after its public collection and possible sorting, through domestic or on-site treatments (e.g. home or community composting) and through waste prevention activities, is therefore the same in all compared scenarios. In fact, in each of them, the sum of the amount of waste generated and of that prevented is identical. In particular, it is defined as the amount of waste potentially producible in the area (or system) under study, as better explained in Section 5.2.

In the second approach (*Approach 2*) waste prevention is not considered as a real waste management method and, therefore, the amount of waste to be managed (only through conventional or domestic/on-site treatments) varies among the analysed baseline and waste prevention scenarios, as a consequence of the implementation of waste prevention activities.

5.2 Functional unit

According to *Approach 1*, the functional unit is defined as:

"*the integrated management of the waste potentially producible over a given period in a given geographical area* (*or by one of its inhabitants*), *in which waste prevention activities will be undertaken*", without specifying any amount. An example is "the integrated management of the waste potentially producible during one year by one inhabitant of the Lombardia Region (Italy) in which a waste prevention activity aimed at reducing the consumption of one-way bottled water by citizens will be implemented".

The amount of waste potentially producible in the area under study is identical in all the compared scenarios. It is defined with reference to a baseline scenario, where it corresponds to the amount of waste actually generated and managed through conventional treatments (after public collection and possible sorting), or through domestic and on-site treatments (e.g. home or community composting). In waste prevention scenarios, a portion of the amount of the potentially producible waste (the amount of waste prevented) is instead managed through one or more waste prevention activity(ies).

A functional unit defined as above may be more suitable for the assessment of waste management scenarios concerning specific geographical contexts, whether real or hypothetical, but is less suitable for the evaluation of the consequences of introducing waste prevention in a generic waste management system. In this case, more similarly to a traditional waste management LCA, the functional unit can be alternatively defined as "*the management of a given* (*numerical*) *amount of waste*", such as "the management of 1 tonne of waste", without referring to any specific geographical context. Similarly to the approaches proposed by Gentil et al. (2011) and Cleary (2010), such an amount is then considered to be composed of the amount of waste actually generated and of that prevented and is the same in all compared scenarios. As explained above, in baseline scenarios the whole amount of waste specified by the functional unit is managed through conventional or domestic/on-site waste treatments, while in waste prevention scenarios, a portion of that amount is classified as prevented waste, being managed through one or more waste prevention activity(ies).

In order to allow the comparisons of scenarios where the total amount of waste to be managed is variable, in *Approach 2* the functional unit is instead defined as:

"*the management of the waste produced over a given period in a given geographical area* (*or by one of its inhabitants*)", always without specifying any amount.

In this case, contrary to *Approach 1*, it is not possible to define an alternative functional unit based on a numerical amount of waste to be managed since waste prevention is not considered as a possible waste management method and, as a consequence, the amount of waste to be managed effectively differs among compared scenarios. It is therefore necessary to relate the analysed waste management system(s) to a real or hypothetical geographical context.

5.3 System boundaries

The processes that, according to both *Approach 1* and *Approach 2*, have to be included in the boundaries of the waste management system in a baseline scenario and in a waste prevention one including *n* waste prevention activities of each of the different typologies reported in Table 1 are schematically represented in Fig. 1.

First of all, according to both approaches, as for traditional LCA of waste management, system boundaries include, in both a baseline and a waste prevention scenario, the collection, possible sorting and subsequent conventional treatment processes (mechanical and biological treatments, recycling, thermal treatments and landfilling) as well as the possible domestic or on-site treatments (e.g. home or community composting), of all the waste streams effectively generated in such scenarios in the studied area/system during the considered period of time. The part of the waste management system that includes such downstream processes is defined as *waste treatment system* (WTS, see Fig. 1), which, according to *Approach 1*, in a baseline scenario will coincide with the waste management system.

In particular, in order to evaluate the downstream consequences (i.e. the consequences on the impacts involved by the processes taking place after the waste has been generated) of the considered waste prevention activities, the waste treatment system of a baseline scenario has to include at least the treatment processes of all the waste goods and packaging that will be prevented in waste prevention scenario(s). Instead, the waste treatment system of a waste prevention scenario has to include at least the treatment processes of all the substitutive goods and packaging that can be generated as additional waste to be managed as a consequence of the implementation of the considered waste prevention activities. Examples of prevented and substitutive waste goods and packaging are reported in the last two columns of Table 1 for the different typologies of waste prevention activities identified. It is important to notice that when waste prevention activities based on reuse of disposable goods in substitution of durable goods (type 7 activities), as well as on reuse and lifespan extension of existing durable goods (types 8 and 9 activities) are implemented, in the last resort the prevented waste is not represented by the reused

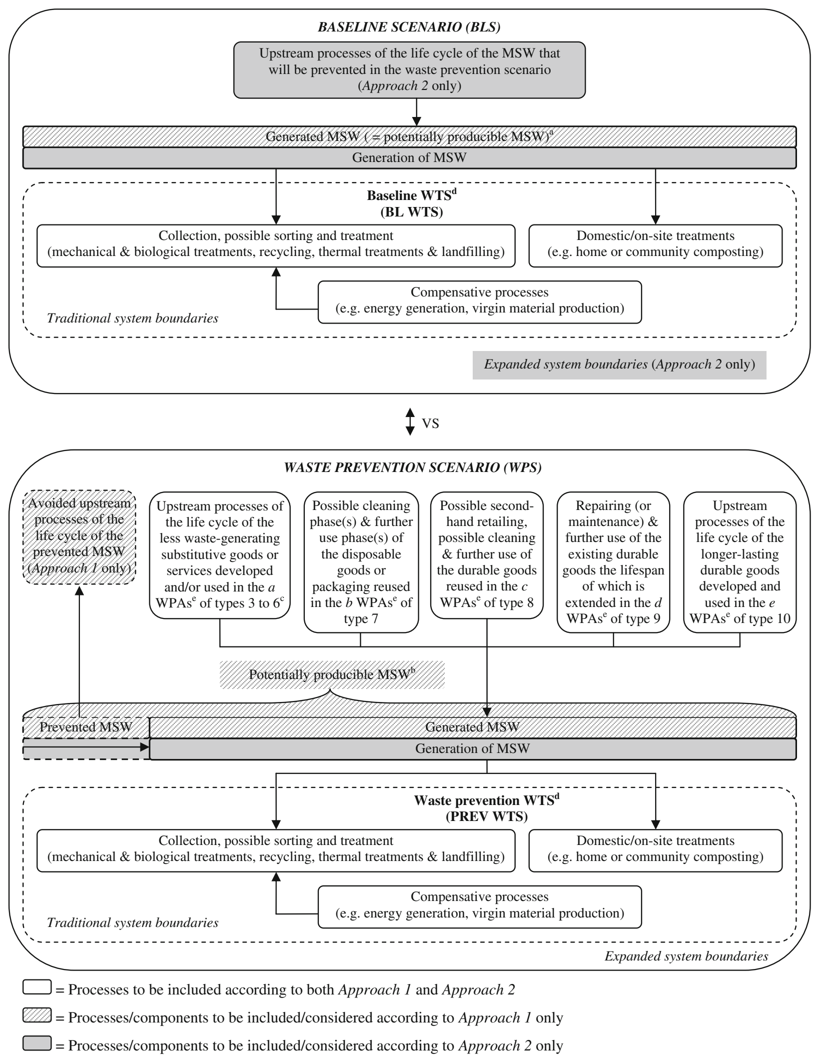

Fig. 1 Major processes to be included, according to the presented approaches (*Approach 1* and *Approach 2*), in the system boundaries in a waste prevention scenario that includes *n* waste prevention activities and in a respective baseline scenario. Out of the *n* waste prevention activities, *a* is of types 3 to 6, *b* of type 7, *c* of type 8, *d* of type 9, and *e* of type 10 (according to the typologies reported in Table 1)

[a] According to *Approach 1*, in baseline scenarios the whole amount of waste potentially producible in the studied area/system is actually generated as waste and, therefore, the two amounts are identical

[b] According to *Approach 1*, in waste prevention scenarios a portion of the amount of waste potentially producible in the studied area/system is prevented, so that the respective amount is greater than the amount of waste actually generated

[c] Goods or packaging using less material (type 3 activities), unpacked goods (type 4 activities), reusable goods or goods provided in reusable packaging (type 5 activities) and digital goods (type 6 activities)

[d] WTS: Waste treatment system [e] WPA: Waste prevention activity

goods or by the goods the lifespan of which has been extended, but by those equivalent new durable goods that would be used (and wasted at the end of their useful life) if reuse or lifespan extension activities were not undertaken[1] (Joint Research Centre of the European Commission 2011). Therefore, one should take into account that equivalent new goods may be composed of different materials compared to more outdated reused ones (e.g. furniture using more environmentally friendly adhesives and resins or electric and electronic equipment using parts made up of different metals).

According to *Approach 1*, in waste prevention scenarios, system boundaries of traditional waste management LCA are also expanded upstream to include all the upstream processes avoided thanks to the implementation of the considered waste prevention activities and all the additional upstream processes that take place as a consequence of the implementation of such activities, and for which the 'zero burden' assumption cannot be maintained. In fact, the management of the prevented waste (goods or packaging) through one or more waste prevention activity(ies) (which according to *Approach 1* are considered to be an actual waste management method), involves the

[1] Actually, an equivalent new good is prevented in its entirety only if its average lifespan is identical to the duration of the second life of the reused good, or of the additional life of the good the lifespan of which has been extended. If these latter are shorter or longer than the former, only a fraction (smaller or greater than 1) of the equivalent new good is actually prevented. It is equal to the ratio between the duration of the second life of the reused good (or the duration of the additional life of the good the lifespan of which has been extended) and the average lifespan of the equivalent new good. This is not very close to the reality, where waste is defined by integer quantities, but it is a possible modelling approach also reported in the guidelines prepared by the Joint Research Centre of the European Commission (2011).

following upstream consequences. First of all, the processes belonging to the whole upstream life cycle of the prevented waste (raw material extraction, material production, product manufacture, distribution and use) are generally avoided. Moreover, additional upstream processes take place when waste prevention activities of types 3 to 10 are implemented. In the case of types 3 to 6 activities, such additional processes are those associated with the whole upstream life cycle of the less waste-generating substitutive goods or services that will be developed and/or used, i.e. goods or packaging using less material (type 3 activities), unpacked goods (type 4 activities), reusable goods or goods provided in reusable packaging (type 5 activities) and digital goods (type 6 activities). In the case of type 7 activities, a cleaning phase of the reused disposable goods or packaging (e.g. bottles) may have to be performed before (each of) their further utilisation cycle(s), although the burdens associated with these two phases are generally limited and probably negligible. In the case of type 8 activities, additional processes are represented by the operation of possible second-hand shops, by the possible cleaning phase of the reused durable goods, as well as by their further use phase (which generally has relevant impacts only if they use consumables). For type 9 activities, possible repairing or maintenance operations of the existing durable goods the lifespan of which will be extended and their further use phase are involved, as well as, for type 10 activities, the whole upstream life cycle of the longer-lasting durable goods that will be used. All these upstream processes and any other upstream process that may be affected by the implementation of the considered waste prevention activities have to be therefore included in the system boundaries in a waste prevention scenario, unless their effect on the resulting impacts is negligible.

According to *Approach 2*, since the amount of waste generated in waste prevention scenario(s) is different from that generated in the compared baseline scenario(s), the 'zero burden' assumption is, in general, no longer valid, and traditional system boundaries are expanded upstream in both baseline and waste prevention scenarios in order to include those upstream processes that differ among such scenarios for their typology or magnitude. For a baseline scenario, such upstream processes are those belonging to the whole upstream life cycle of the waste (goods or packaging) that will be prevented in waste prevention scenario(s) thanks to the implemented activities and the end-of-life of which is already included in such a baseline scenario. For a waste prevention scenario they are represented by the additional upstream processes that take place as a consequence of the implementation of types 3 to 10 waste prevention activities, and already reported in the above paragraph of the present section during the description of the system boundaries to be adopted in a waste prevention scenario according to *Approach 1*.

Therefore, in practice, according to *Approach* 2 a baseline scenario includes implicitly the whole life cycle of the waste (goods or packaging) that will be prevented in waste prevention scenario(s). Instead, depending on the typology of prevention activity, a waste prevention scenario includes implicitly the whole life cycle of the developed/used less waste-generating substitutive goods or services (types 3 to 6 activities), the part of the life cycle that takes place after the first utilisation cycle of reused disposable goods or packaging (type 7 activities), the second life of the disposable goods or packaging reused in place of durable goods (type 7 activities), the second life of reused durable goods (type 8 activities), the additional life of durable goods the lifespan of which has been extended (type 9 activities) and the whole life cycle of used longer-lasting durable goods (type 10 activities)[2].

In principle, the whole upstream life cycle of all the generated waste streams should be included in the system boundaries in all of the compared scenarios; however, in a comparative analysis (such as the one between baseline and waste prevention scenarios) identical parts, i.e. the upstream processes the magnitude of which is not affected by waste prevention activities, can be omitted.

An approach similar to *Approach 2* has been used by Matsuda et al. (2012), who evaluated the consequences of reducing edible food waste (food loss) by 36.8 % on greenhouse gases emissions associated with the management of household combustible waste arising from the city of Kyoto. To this aim the authors compared two scenarios, with and without the partial prevention of food loss, and both of them included, besides collection and treatment of all the waste streams generated in such scenarios, also the processes of production, distribution and cooking of the whole amount of food loss generated in the same scenarios. In a small variant of this, and following *Approach 2*, only the boundaries of the baseline scenario are expanded to include the processes belonging to the upstream life cycle of the food loss that will be prevented, while no upstream processes are included in the waste prevention scenario. In fact, since the upstream life cycle of not prevented food loss is identical in both waste prevention and baseline scenarios, it can be omitted without affecting their comparison. Such an approach is useful especially when only the amount of waste which can be potentially prevented through a given activity is known, but not the overall amount of the waste fraction targeted for prevention (i.e. in the example, only an estimation of the amount and of the composition of preventable food loss is known, but not the overall amount of food loss generated in the baseline case).

In conclusion, in *Approach 1* all the upstream processes affected by waste prevention activities are included in system boundaries, as avoided and additional processes, in waste prevention scenarios (just because they are the processes

[2] This is valid also for *Approach 1*, even if not explicitly stated during the description of the system boundaries adopted in a waste prevention scenario according to this approach.

avoided or involved by managing the prevented waste through one or more prevention activity(ies)). Conversely, in *Approach 2*, such affected upstream processes are included, as additional processes, in the scenario in which they actually occur (since they are the processes which differ among compared scenarios because of waste prevention activities). Therefore, apart from the different theoretical premises according to which upstream system boundaries are derived for baseline and waste prevention scenarios in the two approaches, from the practical point of view they essentially differ in the following: according to *Approach 1* the upstream processes of the life cycle of the prevented waste are included, as avoided processes, in waste prevention scenarios, while in *Approach 2* they are included as additional processes in the baseline scenario in which they take place (i.e. where the waste that will be prevented is generated).

5.4 Environmental impacts calculation

The procedure to be used, according to both *Approach 1* and *Approach 2*, for the calculation of the environmental impacts of a baseline and a waste prevention scenario reflects the boundaries considered for the waste management system in such scenarios by the two approaches.

As specified by Eq. 1, according to *Approach 1* the impacts of a baseline scenario (BLS) coincide with the impacts of the respective baseline waste treatment system (BL_WTS) which, in this approach, is the unique component of the waste management system in baseline scenarios. It includes collection, possible sorting and conventional treatment processes (as well as the possible domestic or on-site treatments) of all the waste streams generated in the baseline scenario under analysis, and its impacts can be calculated with a traditional waste management LCA of the baseline waste treatment system itself:

$$\mathrm{BLS} = \mathrm{BL\_WTS} \tag{1}$$

According to *Approach 2*, the impacts of a baseline scenario of a system in which n waste prevention activities will be implemented, are instead calculated as follows (Eq. 2):

$$\mathrm{BLS} = \mathrm{BL\_WTS} + \sum_{i=1}^{n} \mathrm{UpP\_PW_i} \tag{2}$$

where the terms BLS and BL_WTS have the same meaning as in Eq. 1, while $\mathrm{UpP\_PW}_i$ represents the impacts of the upstream processes (raw material extraction, material production, product manufacture, distribution and use) of the life cycle of the waste that will be prevented in waste prevention scenario(s) thanks to the implementation of the ith waste prevention activity.

According to *Approach 1*, the impacts of a waste prevention scenario in which n waste prevention activities (of which m of types 3 to 10) are implemented, are calculated with the following equation (Eq. 3):

$$\mathrm{WPS} = \mathrm{PREV\_WTS} - \sum_{i=1}^{n} \mathrm{UpP\_PW_i} + \sum_{j=1}^{m} \mathrm{Add\_UpP_j} \tag{3}$$

where:

- WPS=particular impact of a waste prevention scenario including n waste prevention activities (of which m of types 3 to 10);
- PREV_WTS=particular impact of the waste prevention waste treatment system, i.e. of the part of the waste management system that includes collection, possible sorting and conventional treatment processes (as well as the possible domestic or on-site treatments) of all the waste streams generated in the waste prevention scenario under analysis. It can be calculated with a traditional waste management LCA of the waste prevention waste treatment system itself;
- $\mathrm{UpP\_PW}_i$=as in Eq. 2, particular impact of the (avoided) upstream processes (raw material extraction, material production, product manufacture, distribution and use) of the life cycle of the waste prevented thanks to the implementation of the ith waste prevention activity;
- $\mathrm{Add\_UpP}_j$=particular impact of the additional upstream processes that take place as a consequence of the implementation of the jth waste prevention activity of types 3 to 10.

According to *Approach 2*, the impacts of a waste prevention scenario that includes n waste prevention activities, of which m of types 3 to 10, are instead calculated as follows (Eq. 4):

$$\mathrm{WPS} = \mathrm{PREV\_WTS} + \sum_{j=1}^{m} \mathrm{Add\_UpP_j} \tag{4}$$

where all the terms have the same meaning as in Eq. 3 (*Approach 1*) but, compared to this, excludes the avoided impacts of the upstream processes of the life cycle of the waste prevented thanks to all the n implemented waste prevention activities ($\sum_{i=1}^{n} \mathrm{UpP\_PW_i}$). In fact, according to the system boundaries considered by *Approach 2*, the impacts of such upstream processes have already been included, with a positive sign, in Eq. 2, which is used to calculate the impacts of a baseline scenario when such an approach is used.

If out of the m waste prevention activities of types 3 to 10 included in a waste prevention scenario, a is of types 3 to 6,

b of type 7, *c* of type 8, *d* of type 9 and *e* of type 10 (with $a+b+c+d+e=m$), the last term of Eqs. 3 and 4 can be better expressed as follows (Eq. 5):

$$\sum_{j=1}^{m} \mathrm{Add\_UpP_j} = \sum_{k=1}^{a} \mathrm{Add\_UpP_k} + \sum_{l=1}^{b} \mathrm{Add\_UpP_l} + \sum_{p=1}^{c} \mathrm{Add\_UpP_p} + \sum_{q=1}^{d} \mathrm{Add\_UpP_q} + \sum_{r=1}^{e} \mathrm{Add\_UpP_r} \quad (5)$$

where:

$\mathrm{Add\_UpP}_k$=impact of the upstream processes of the life cycle of the less waste-generating substitutive goods or services developed and/or used in the *k*th waste prevention activity of types 3 to 6 (goods or packaging using less material, unpacked goods, reusable goods or goods provided in reusable packaging, digital goods);

$\mathrm{Add\_UpP}_l$=impact of the possible cleaning phase(s) and of the subsequent use phase(s) of the disposable goods or packaging reused in the *l*th waste prevention activity of type 7;

$\mathrm{Add\_UpP}_p$=impact of possible second-hand retailing, possible cleaning and of the further use phase of the durable goods reused in the *p*th waste prevention activity of type 8 (generally, the impact of the use phase is relevant only if the reused goods use consumables);

$\mathrm{Add\_UpP}_q$=impact of the possible repairing or maintenance phase(s) and of the further use phase of the existing durable goods the lifespan of which is extended in the *q*th waste prevention activity of type 9 (generally, the impact of the use phase is relevant only if the goods the lifespan of which is extended use consumables);

$\mathrm{Add\_UpP}_r$=impact of the upstream processes of the whole life cycle of the longer-lasting durable goods developed and used in the *r*th waste prevention activity of type 10.

To calculate the net impacts associated with the implementation of the considered waste prevention activities, and with any possible change in the management of the remaining MSW (e.g. a variation of separated collection efficiencies), the impacts of a baseline scenario (Eq. 1 or 2, depending on the used approach) have to be subtracted from those of a waste prevention scenario calculated with Eq. 3 or 4. This difference is identical either when it is calculated with one approach or the other since, from the mathematical standpoint, the equations adopted by the two approaches include the same terms overall, with the only difference that, in *Approach 1*, the term representing the impacts of the upstream processes of the life cycle of the waste prevented thanks to the implementation of the considered waste prevention activities is included with a negative sign in the equation used to calculate the impacts of a waste prevention scenario (Eq. 3), while in *Approach 2*, it is included with a positive sign in the equation used to calculate the impacts of a baseline scenario (Eq. 2). Therefore, both the approaches are equivalent in terms of obtained solution, even if their application is more suitable in different situations, as we will discuss more extensively in Section 6.

5.5 Example

To illustrate the definition of the system boundaries when using the two presented approaches (*Approach 1* and *Approach 2*) consider the case where a waste prevention activity consisting in drinking of tap water instead of one-way bottled water (type 4 activity) is undertaken by a certain number of citizens of a given municipality.

According to *Approach 1*, in a baseline scenario (in which no waste prevention activities are undertaken) system boundaries have to include at least the end-of-life phase (collection, possible sorting, treatment and the possibly associated compensative processes) of the one-way water bottles, caps and labels that will be prevented by drinking tap water.

In a waste prevention scenario, system boundaries will instead firstly include the end-of-life phase of any goods generated as waste as a consequence of the consumption of public network water (e.g. reusable jugs or bottles) and of any other waste stream possibly considered in the baseline scenario. Moreover, they are also expanded to include the upstream processes that are avoided and that take place as a consequence of the consumption of tap water. Avoided upstream processes are those belonging to the whole upstream life cycle of prevented one-way water bottles and specifically represented by their manufacturing, filling, capping, labelling, packing in bundles, palletisation, transportation, distribution and use, including manufacturing of the goods employed in these activities (caps, labels, secondary and transport packaging) and their end-of-life if not already included among downstream processes. Additional upstream processes to be included as well in the system boundaries in a waste prevention scenario are instead those belonging to the whole upstream life cycle of an amount of tap water identical to the volume of water packaged into prevented one-way water bottles and specifically represented by its collection, purification, distribution and use, including manufacturing of the goods used in these activities (e.g. chemicals, activated carbon, reusable jugs or bottles) and their end-of-life if not already included among downstream processes.

From the practical point of view, if *Approach 2* is instead used, the only difference compared to *Approach 1* is that the upstream processes belonging to the whole upstream life cycle of prevented one-way water bottles are not included as avoided processes in a waste prevention scenario, but as additional processes in a baseline scenario which also includes the end-of-life of such bottles. In this case, in fact, the system boundaries are expanded in both the baseline scenario and the waste prevention one in order to include the upstream processes that differ from one to the other due to the fact that tap water is drunk instead of one-way bottled water.

6 Discussion

Two different LCA approaches (*Approach 1* and *Approach 2*) to evaluate the environmental and energetic performance of MSW management scenarios that include waste prevention activities are described. They differ in the perspective from which they look at waste prevention activities with respect to the waste management system (Section 5.1) and in the functional unit consequently adopted (Section 5.2) but, although on the basis of different premises and in different scenarios, both of them foresee the expansion of traditional system boundaries of waste management LCA to include the upstream processes affected by the considered waste prevention activities (Section 5.3) and the associated impacts (Section 5.4). The only difference is that, while in *Approach 1* the upstream processes of the life cycle of the prevented waste and their impacts are included as avoided processes/impacts in waste prevention scenarios, in *Approach 2* they are included as additional processes/impacts in the baseline scenario where they actually occur.

For this reason, both the approaches provide the same result in terms of difference between the impacts of a waste prevention scenario and of a baseline one, which represent the net impacts associated with the implementation of the considered waste prevention activities and with any possible change in the management of not prevented MSW. They lead therefore to the same overall conclusion when the performance of a waste prevention and a baseline scenario are compared. Nevertheless, because of the partially different upstream system boundaries considered in baseline and waste prevention scenarios, the LCA results of single scenarios calculated with *Approach 1* are different from those calculated with *Approach 2*. For the same reason, the interpretation of scenarios' results (in particular those referring to baseline scenarios), as well as their comparison aimed at identifying the consequences of implementing the considered waste prevention activities, need to be carried out differently. Moreover, the utilisation of the two approaches can be more suitable in different situations and in studies with different purposes. We will therefore now discuss these three points, starting from the assessment of the consequences of waste prevention activities on downstream and upstream impacts.

Both approaches include in the system boundaries the same downstream processes either in baseline or in waste prevention scenarios (i.e. the management processes of the many MSW streams generated in such scenarios). Therefore, in order to identify and calculate the net consequences of the considered waste prevention activities on downstream impacts, one has to compare, with both the approaches, the impacts of downstream processes in a waste prevention scenario with those of downstream processes in a respective baseline scenario. A comparison among the overall impacts of downstream processes is appropriate only if no changes in the management of not prevented MSW take place in the waste prevention scenario with respect to the baseline scenario. Otherwise, in order to distinguish the downstream consequences of waste prevention activities from those of any changes in the management of not prevented MSW, the impacts from the management processes of the prevented waste (in baseline scenarios) and of the possible substitutive waste streams (in waste prevention scenarios) should be isolated from the impacts associated with the management of the other waste streams.

As explained in Section 5.3 and earlier in the present section, according to *Approach 1* all the upstream processes affected by waste prevention activities and the associated impacts are included in waste prevention scenarios as avoided and additional processes/impacts. By using this approach it is thus possible to directly identify in the LCA results of a waste prevention scenario, the upstream impacts (loads) and the avoided upstream impacts (benefits) of the considered waste prevention activities, and to subsequently calculate their net consequences on upstream impacts. According to *Approach 2*, the upstream processes affected by waste prevention activities and their impacts are instead included as additional processes/impacts in the scenario in which they actually occur. In this case, the net consequences of the considered waste prevention activities on upstream impacts are calculated by subtracting the impacts of the upstream processes included in baseline scenarios from the impacts of the upstream processes included in waste prevention scenarios.

Regarding the interpretation of the LCA results of single scenarios, when *Approach 1* is adopted, the absolute impacts of a baseline scenario represent, as usual in waste management LCA, the impacts of managing the different waste streams generated in such a scenario according to a given treatment scheme, since no upstream processes are included in the system boundaries in such a scenario. On the contrary, if *Approach 2* is used, the impacts of a baseline scenario are deviated by the positive contribution provided by the upstream processes belonging to the life cycle of the prevented waste. Therefore, more caution is needed in the possible interpretation of the LCA results of a baseline scenario in isolation from the LCA results of the associated waste prevention scenario(s), which may be less straightforward for a waste manager or policy maker, due to the inclusion of specific upstream processes that apparently have no direct connection with waste management.

Focussing on the applicability of the two approaches, generally speaking, the use of *Approach 1* is more suitable if there is an interest in accounting for the upstream consequences/impacts of waste prevention activities only in waste prevention scenarios, if a method based on the concept of avoided and additional impacts is preferred, and if the LCA results of baseline scenario(s) need to be also interpreted singularly, other than in the comparison with

the LCA results of the respective waste prevention scenario(s). More specifically, *Approach 1* is preferable when more (baseline) scenarios without waste prevention activities, distinguished only by variations in the management method of the same waste streams, need to be contemporarily compared with one or more waste prevention scenarios. In this case (in contrast to *Approach 2*), no upstream processes that would remain unchanged from one baseline scenario to the other would be included in the system boundaries in such scenarios, thus facilitating both the interpretation of the LCA results of baseline scenarios themselves and their comparison. An example is a study to evaluate whether the partial replacement of landfilling of specific waste fractions with their high-efficiency incineration or their partial prevention through specific activities would be more beneficial. In this case, a baseline scenario mainly relying on landfill would be compared either with an alternative scenario without waste prevention where landfilling is partially replaced by incineration, or with a waste prevention scenario where a partial prevention of landfilled waste is introduced.

Finally, the use of *Approach 1* is also preferable when the impacts of individually implementing different waste prevention activities in a given waste management system need to be mutually compared. In this case, by applying *Approach 1*, only one baseline scenario would have to be modelled and, subsequently, individually compared with each of the waste prevention scenarios where the different waste prevention activities to be assessed are singularly implemented. If *Approach 2* was instead used, a baseline scenario would have also to be modelled for each considered waste prevention activity, which includes the upstream processes of the life cycle of the waste that will be prevented thanks to that particular activity.

Approach 2 is instead more suitable when (a) there is an interest in accounting for the impacts of the upstream processes affected by waste prevention activities in the scenario in which they actually occur, (b) an independent assessment of the impacts of all (or part of) the activities that can be implemented for the prevention of a given typology of waste is required and, (c) the practitioner intends to compare the consequences of preventing different types of waste (e.g. bottles made of different materials) through a given activity, assuming in each case a complete prevention of the targeted waste stream. For instance, with regard to this last point, one may be interested in evaluating the benefits of drinking tap water instead of drinking water packaged in bottles of different materials, such as virgin PET, partly recycled PET and polylactic acid (PLA). In this case, according to *Approach 2*, three baseline scenarios would be modelled first (one for each typology of material). Their system boundaries would include, among the other possible downstream processes, the end-of-life of water bottles that will be prevented thanks to the use of tap water, and the associated upstream processes (from manufacturing to use by citizens). These scenarios would then be singularly compared with a unique waste prevention scenario, where the stream of waste water bottles is completely removed and the end-of-life of the additional waste streams possibly generated by the use of tap water is included, together with all the upstream processes associated with the use of tap water itself (from purification to use by citizens). If *Approach 1* was instead used, other than three baseline scenarios (each one including, among the other possible downstream processes, the end-of-life phase of water bottles made out of one of the three different considered materials), also three waste prevention scenarios would have to be modelled, each one including, besides the other downstream and upstream processes considered in *Approach 2*, the avoided upstream processes of the life cycle of water bottles of one of the three considered materials, prevented thanks to the use of tap water. Each waste prevention scenario would then be singularly compared with the respective baseline scenario. However, if only a fraction of the stream of waste water bottles was assumed to be prevented, even the application of *Approach 2* would require the modelling of three different waste prevention scenarios. In fact, each time, not prevented water bottles would be of a different material and their end-of-life would likely be different. With regard to point (b), we can instead consider that, for instance, the production as waste of one-way water bottles can be prevented either by the use of tap water or of refillable bottled water, while that of paper hand towels either by the use of electric hand-dryers or of tissue hand towels. The independent quantification of the impacts of the different activities that can be implemented to prevent a particular typology of waste with *Approach 1* would require the inclusion of the same avoided upstream processes (the typology of prevented waste is the same) in all of the waste prevention scenarios to be modelled (one for each considered activity). By using *Approach 2* it is instead possible to include such upstream processes only once, as additional processes, in a baseline scenario, thus simplifying the modelling of the different waste prevention scenarios.

The applicability of the presented approaches, necessary to evaluate scenarios including waste prevention activities, can be more complex than traditional waste management LCA for a number of factors, the first of which is represented by the modelling of upstream processes. For many of them (e.g. packing of products, product assembly etc.) an inventory is not available in the most widespread databases and, in some cases, it can be difficult to gather reliable life cycle data for its development. This involves the need to deal with further subjects beyond the operators of the waste management sector, thus making the data collection stage more time consuming than in traditional waste management LCA. Moreover, some upstream processes take place in foreign countries (e.g. product manufacturing or assembly in the Far East) or in more countries and their proper modelling can be a complex task. Conversely, traditional waste management systems are

generally "local" systems, since waste treatment processes often take place within a district or at a regional level. It is therefore less challenging to carry out the data collection stage, which usually allows one to obtain primary data actually representative of the system to be modelled. Another drawback of including upstream processes in the boundaries of the analysed systems is the potential introduction of greater uncertainty in the LCA results.

A second factor that can make the application of the presented approaches more complex is the evaluation of the overall amount of waste that can be potentially prevented thanks to the considered activities (usually referred to as waste prevention potential), which is another additional step to be performed compared to traditional waste management LCA. Estimations of such a parameter (generally expressed in kilograms of waste prevented per inhabitant per year or as percentage reduction of the targeted waste fraction) are available for different waste prevention activities, based on the results of real experiences implemented in different regions (Salhofer et al. 2008; ACR+ 2010) or derived from calculations on consumption and waste generation data regarding particular areas and contexts (Salhofer et al. 2008). However, their applicability to the studied area should be checked with new site-specific estimations based on the actual consumption patterns that lead to the generation of the different types of waste to be prevented and on the expected participation rates of the actors (citizens, organisations, retailers, producers etc.) who are requested to undertake the considered waste prevention activities (e.g. by changing their consumption behaviour). A survey may be carried out in the area under study to estimate such participation rates. In particular, a survey would be of help when more activities can be implemented to prevent a given type of waste, i.e. generally, when different less waste-generating goods can be used in substitution of the one generating the prevented waste. In this case, a survey would allow estimating the percentage of actors that will prefer to implement one activity rather than the other. Moreover, it would allow identifying the extent to which the prevented good would be potentially substituted by one less waste-generating equivalent good rather than the other and, therefore, the extent to which the associated upstream and downstream processes would have to be included in the system boundaries.

A last critical aspect associated with the application of the presented approaches is just due to the fact that, in some cases, the extent to which the processes belonging to the life cycle of a less waste-generating good have to be included in the system boundaries in a waste prevention scenario is not immediately identifiable. This generally happens when substitutive goods are digital goods. For instance, if a supermarket chain completely replaces printed advertising brochures with digital ones, it is not straightforward to determine the time spent overall by consumers at reading all the brochures that will be consulted on-line, which establishes the magnitude with which the upstream process associated with the activity 'use of a personal computer' have to be taken into account in a waste prevention scenario.

7 Conclusions

The environmental and energetic performance of MSW management scenarios that include waste prevention activities can be evaluated in a life cycle perspective with the two approaches presented in this paper. They allow one to evaluate whether and/or under what conditions, a reduction in waste generation is actually accompanied also by a reduction in the impacts on the environment and the human health. This is especially important when waste prevention is not achieved through the simple reduction of the consumption of given goods or services, but through the use of less waste-generating substitutive goods or services, reuse or lifespan extension. In this case, in fact, along with waste reduction and the associated upstream and downstream benefits, additional upstream and downstream[3] impacts are involved. Member States of the European Union should therefore support the preparation of national waste prevention programmes with the use of LCA tools, in order to guide the choice of prevention measures and the way in which they can be best implemented so that additional environmental impacts are not involved.

An LCA-based quantification of the potential environmental benefits of a prevention activity allows one to evaluate its effectiveness without referring only to the amount of potentially preventable waste. In fact environmental benefits may not be linearly correlated with the amount of waste prevented (i.e. a small reduction in waste amount can lead to a significant reduction in impacts ad vice versa) and waste reduction indicators should be used in combination with LCA indicators for a comprehensive picture. For instance, higher downstream benefits can be expected from the prevention of a given waste type containing hazardous substances (e.g. batteries, electronic equipment etc.) compared to the prevention of the same amount of a less hazardous waste type, due to the reduction of direct emissions of hazardous substances.

According to the European directive on waste (European Parliament and Council 2008), the aim of waste prevention measures should be the decoupling between the economic growth and the environmental impacts associated with the generation of waste. The availability of tools to quantitatively assess the environmental benefits of waste prevention activities can be therefore useful also to perform decoupling evaluations and, more in general, to provide quantitative evidence in support of the relevance of waste prevention in waste management policies and strategies.

[3] In the case of reuse and lifespan extension of existing goods only additional upstream impacts are generally involved.

More in detail, the two presented approaches are therefore useful to: (a) quantify the overall environmental and energetic consequences of implementing one or more waste prevention activity(ies) in a system where waste is managed according to a given treatment scheme (*Approach 1 or 2*); (b) compare the consequences of individually implementing different waste prevention activities or, however, of preventing different types of waste without referring to any particular prevention activity, in a given waste management system (*Approach 1*); (c) assess the consequences of implementing the same waste prevention activity(ies) (or of preventing the same type(s) of waste) in different waste management systems (*Approach 1* if one intends also to compare the performance of baseline scenarios of the different waste management systems, otherwise even *Approach 2* is suitable); (d) evaluate whether greater environmental benefits are achieved by introducing specific levels of waste prevention in an existing waste management system or by optimising its performance without introducing waste prevention (e.g. by increasing material and energy recovery, reducing distances etc.; *Approach 1*); (d) evaluate the consequences of implementing one or more waste prevention activity(ies) on the optimal management option for a constant amount and composition of waste (*Approach 1*); (e) evaluate the consequences of preventing the same type of waste through different activities (*Approach 2*) and (f) evaluate the consequences of preventing different types of waste (e.g. bottles made of different materials) through a given prevention activity (*Approach 2* if a 100 % prevention of the targeted waste stream is considered, otherwise even *Approach 1* is suitable).

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